DEVELOPMENT OF A CREEPING LOMOTION SNAKE ROBOT

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Abstract

Biological snakes' diverse locomotion modes and physiology make them supremely adapted for the environment. The special structure of snakes and their unique movement offer them peculiar ability of climbing and moving even in some ill-conditioned environments, such as on the marshland or in narrow tubes. Using these snakes' noticeable features into robots is becoming more important for generating a new type of locomotor and expanding the function of robots. In this article, we introduce a 12-link snake-like robot, which is moved through the difference between normal and tangential friction. The propelling force of our robot is generated only by swinging its joints from side to side.

Key Words

Snake, snake-like robot, creeping locomotion, environment adaptability, optimal locomotion shape

1. Introduction

Snakes perform many kinds of movement adapted to the environment. Instead of being handicaps, the lack of limbs, the considerable elongation of the body, and the particular mode of locomotion have allowed snakes to expand into diverse environments. One of the snakes' assets is their ability to immediately respond to a new environment by changing modes. In our study, we try to develop a snake-like robot, which utilizes the natural locomotion of snakes.

Snakes are so diversified that they include many examples of specialization, in which one lateral undulation mode is favoured. When these lateral undulations are broadly classified, there exist four gliding modes:

(1) serpentine movement
(2) rectilinear movement
(3) concertina movement
(4) side winding movement

However, the serpentine movement (creeping locomotion) is the movement seen typically in almost all kinds of snakes, and is a gliding mode whose characteristic is that each part of the body leaves similar tracks. In this study, we thus selected the serpentine movement as the elective movement for our robot.

Snakes as a biological machine, in spite of their simplicity, has higher performance by changing its highly redundant body to adapt to the environment. The snake-like robot utilizes snake-like characteristics, thus, can perform the following functions:

- It can propel itself over an uneven/rough ground, and swim in a fluid by using its slender body.
- Snake-like robot can creep on a soft ground, such as marshland or sand dunes, because it can distribute its weight over its whole body.
- It can move across branches or crevasses, because it can tighten its body to make a kinematically stable posture by using its long body and highly redundant actuators.
- It can manipulate objects by using its highly flexible body as a hand.

Because of these advantages, snake-like robots are potentially superior for operations in highly constrained and unusual environments encountered in applications, such as inspection of nuclear reactor cores and chemical sampling of buried toxic waste, where high adaptability is required.

A thesis about snake-like robot's motive force, that the joints of the snake-like robot are swung and its propelling force is generated through the difference between normal and tangential frictions, had been advanced in our previous article [1]. After that, we set about realizing this principle in our robot. In this study, based on our investigation, we developed a snake-like robot without any forward direction driving force. The wheel installed under the link plate along the forward direction is for providing a contact point with the ground and generating the difference between normal and tangential friction. The frictional force is small along the link direction, and large in the direction normal to the
link. The joints of the developed snake-like robot are only rotated from side to side by electrical motors. Our robot exactly moves with this swinging motion input of joints. In this article, we also introduce a control procedure for the serpentine movement. Some results of finding the efficient locomotion's patterns are shown as well.

The article is organized as follows. Section 2 reviews the previously developed snake-like robots, and Section 3 presents the mechanism of the newly developed snake-like robot and its control system. Section 4 gives the experimental results of our robot. Finally, Section 5 gives the conclusions of the article.

2. Review of Previously Developed Snake-Like Robots

Because of the snake's high adaptability to the environment, the research of snake-like robots is more and more active now. One of the earliest studies on snake-like robots was conducted by Hirose. He built the first snake-like robot (ACM III) in 1974, made up by a set of links and joints with the capability of propelling itself forward only by internal joint torque input [2]. Each joint consists of servo-mechanisms that can bend to the left and right. The casters installed on the joints were only for making contact with the ground, and characteristics were added that made it easy to slide in the tangential direction of forward and difficult to slide in the normal direction. This initial study was limited to 2-D motion. Thereafter, the Hirose group continued their work on the ACM-R1. They conducted gliding experiments on ice with different edges instead of wheel and terrain adaptive locomotion on a slope [3].

More recently, the NEC snake-like robot, which expanded the moving scope to 3-D was developed by NEC in 1996 [4]. The new link model is composed of two degree of freedom (DOF) active universal joint with two actuators and an embedded CPU module with a motor driver. Multiple link modules can be easily attached and detached, because each module is both mechanically and electronically complete in itself. In 1996, almost at the same time, a new flexible GMD-snake, where the kernel of the joint is made of cylindric rubber pieces glued together with aluminium sheets between them, was developed [5]. The "snake" is moved by the bending of the rubber caused by strings' winding or unwinding. The strings run through holes in the metal sheets. Additionally, a hyper-redundant robot named "snakexy" in the VGT structure had also developed [6], and the related researches are being conducted widely [7].

In this study, for the purpose of clarifying the principle of snake-like robot's adaptability to the environment, we developed our snake-like robot to move in 2-D plane with a focus on creeping locomotion.

3. Mechanism and Control System of Newly Developed Snake-Like Robot

As a biological machine, the snake can be seen as a functional body, which connects in series joint units that can bend in an animated manner, and which forms a cord. In this section, we give the mechanism and the control system of our robot in comparison with that of the ACM-R1 [3].

3.1 Mechanism

To show the high expansibility of our snake-like robot, we will discuss the mechanism compared to one of the previously mentioned robot, ACM-R1.

The model and the mechanism of the snake-like robot ACM-R1 is shown in Fig. 1. They are illustrated below:

- The snake-like creeping locomotion curve is separated into several parts. The links are set up with the ends connecting to the joints to adapt to the curve.
- The passive wheel is used to generate the difference of friction force between the normal and tangential direction.
- Passive wheels are set up on joints. To facilitate the tangential direction of locomotion curve, the axles of the passive wheels are designed along the equally divided line of two adjacent links.
- The units are connected by suspension mechanisms, which increase the flexibility of the robot enabling it to move on rough ground.

![Diagram of Robot Mechanism]

Figure 1. (a) Model and (b) mechanism of the ACM-R1 snake-like robot.
Because this structure needs two gears, one for controlling the joint’s angle and the other for adjusting the passive wheel’s direction, it makes the mechanism complicated. Therefore, we developed a snake-like robot, which simplified the mechanism in order to advance the expansibility.

Since many kinds of snake-like robots have been developed, our purpose now is to improve the movability and adaptability in the environment. Our snake-like robot is designed with 12 links. Each active joint, as with the ACM-R1, can bend around the vertical axis.

As shown in Fig. 2, our robot has some new characteristics:

- As with the ACM-R1, the non-drive wheels are chosen to be the connection between our robot and the ground, even though, we are currently still investigating other methods and materials better suited for the ground connection.
- For the purpose of adapting to the snake-like robot’s locomotion curve, in contrast to the ACM-R1, we set links directly along the tangential line through the separated point along the curve.
- The passive wheel is set at the centre of the link in a fixed forward position. With this structure, only one gear is necessary for controlling the joint’s angle. This makes the mechanism quite simple.
- Links are connected by flexible bands to enable our robot to be applicable even on a rough surface.

With this improved and simplified construction, it is much easier to equip our snake-like robot with more devices, such as sensors and so on. Therefore, both the expansibility and adaptability of our robot can be enhanced.

3.2 Control System

The snake-like robot can achieve creeping locomotion only by adjusting the relative angles between adjacent links. These relative angles, which allow the robot’s shape to form along the serpentine curve, are determined by (2), which is given below. The angle signals are converted to voltage through a D/A converter, and then put into the motor drivers on each link, as shown in Fig. 3. This control system was built at a PC/AT (Intel Pentium II 333 MHz, DRAM: 128 MB) by RT-Linux.

![Flow diagram of the control system](image)

Creeping locomotion curve. As discussed in [1], we use the serpentine curve as the basic body shape of the snake-like robot, while it creeps on the plane. The serpentine curve is given by the curvature function:

$$\kappa(s) = \frac{-2K_n \pi \alpha_0}{L} \sin \left( \frac{2K_n \pi}{L} s_p \right)$$

where $K_n$ gives the number of the S-shape, $\alpha_0$ is the initial winding angle, $L (= \sum_{k=0}^{n-1} \delta_k)$ is the whole length of robot body, and $s_p$ is the body length along the body curve, respectively.

![Serpentine body curve](image)

Assume that the snake-like robot holds its shape on the serpentine curve and the body shape changes with respect to the change of the serpentine curve, while moving in the plane. In this case, the joint variables in relative value are derived from integration of the curvature function given.
in (1). In assumption that $\ell_i = \ell$ and $L = n\ell$ ($n$: number of links), the relative angles $\theta_i$ of each joint are determined by:

$$\theta_i(s) = \int_{s+s_{i-1}+\ell/2}^{s+s_{i-1}+\ell/2} \kappa(u) \, du$$

$$= -2a_0 \sin \left( \frac{K_n \pi}{n} \right) \sin \left( \frac{2K_n \pi i}{L} s + \frac{2K_n \pi i}{n} \right) + K_1 \ell$$

(2)

where $K_1$ is the bias curvature to change the creeping locomotion direction, $s$ is the displacement of tail along the serpentine curve path, and $i = 1, 2, \ldots, n - 1$.

Through time differentiation, we can also have the corresponding joint angular velocities $\dot{\theta}_i$ and joint angular accelerations $\ddot{\theta}_i$, that are given by:

$$\dot{\theta}_i(s, \dot{s}) = -\frac{4K_n \pi}{L} a_0 \sin \left( \frac{K_n \pi}{n} \right) \cos \left( \frac{2K_n \pi i}{L} s + \frac{2K_n \pi i}{n} \right) \dot{s}$$

(3)

$$\ddot{\theta}_i(s, \dot{s}, \ddot{s}) = -\frac{4K_n \pi}{L^2} a_0 \sin \left( \frac{K_n \pi}{n} \right) \cos \left( \frac{2K_n \pi i}{L} s + \frac{2K_n \pi i}{n} \right) \ddot{s} + \frac{8K_n^2 \pi^2}{L^4} a_0 \sin \left( \frac{K_n \pi}{n} \right) \sin \left( \frac{2K_n \pi i}{L} s + \frac{2K_n \pi i}{n} \right) \dot{s}^2$$

(4)

where $\dot{s}$ and $\ddot{s}$ are the velocity and acceleration of the tail along the serpentine curve path. Note that, if we use (2)–(4) as the input of the joint variables, not only the constant speed locomotion, but also the accelerated and/or decelerated locomotion can be generated.

**Locomotion control technique.** A method of snake-like robot's control is resuming the time history of the individual joints to be identical but shifted in time. Thus, the robot is treated as a railway-train-like system in which whole body locomotion is following the head in a trace. As shown in Fig. 4(a), the conceptual scheme of control method is: the bending angle of the first joint is stored in data array and the serpentine motion is generated by shifting it backward at fixed time intervals. How big these fixed time intervals are, however, is determined with difficulty. In addition, shifting the angle data backward at fixed time intervals cannot generate the accelerated and/or decelerated locomotion. Both the ACM and GMD snake-like robots chose this control method.

A more general extension of this shifting control method is to represent the joint angles separately at each time step. This kind of control method is not only for periodic forms, but also for locomotion forms where the time history of different joints is not the same, such as the accelerated and/or decelerated locomotion. As seen in Fig. 4(b), our snake-like robot's locomotion is generated by adjusting the joints' variables (joint angles, joint angular velocities, and joint angular accelerations) on the basis of (2)–(4) simultaneously and separately with a time step. This advanced control method enables our snake-like robot to change the moving direction by changing $K_1$ and locomotion speed by inputing the robot motion $s$, $\dot{s}$, $\ddot{s}$, even in the process of motion. That is, giving the joint variables (joint angles, joint angular velocities, and joint angular acceleration) corresponding to the robot motion $s$, $\dot{s}$, $\ddot{s}$, the accelerated and/or decelerated locomotion can be generated. Moreover, this simultaneous control method benefit to feedback every joint's variables detected by sensor to the computer at the same time. Thus, this method provides a more direct flow of information making it easier to control and keep abreast of the robot state in time.

**Start and end of the locomotion.** Assume that the initial shape of snake-like robot is a straight-line chain. Thus, there is a transition gait of locomotion from static state to creeping state, and vice versa. If this transition stage is more smooth, the system is more stable. For starting the locomotion, the initial winding angle is increased gradually from zero to a required value. This change is transmitted in order from the front joint to the end joint. Oppositely, by decreasing the initial winding angle gradually to zero, it can finish the creeping locomotion at a straight-line static state.

4. **Experiment Results**

For observing the different locomotion of our snake-like robot moving on different environment, we carried out the experiment on the environments: one is with friction coefficients $\mu_s = 0.015$ and $\mu_n = 0.6$, another is $\mu_s = 0.2$ and $\mu_n = 0.6$. By measuring the propulsive velocities corresponding to initial winding angle $\alpha_0$ and $S$-shape number $K_n$, we can find the optimal locomotion shape for our snake-like robot to adapt to the given environment.
Figure 5. Propulsive efficiency with respect to $\alpha_0$ and $K_n$: (a) $K_n = 2$ and (b) $K_n = 3$.

Figure 6. Optimal creeping locomotion of our robot on the environment with $\mu_i = 0.015$ and $\mu_n = 0.6$ ($\alpha_0 = 35$ [deg], $K_n = 2$).

Throughout experiment, the joint angular velocity was bounded by its limit value $\pm 0.0006$ [rad/s].

From the results shown in Fig. 5, we know that, no matter what value the $S$-shape number $K_n$ is, the fastest propulsive velocity is achieved on, $\alpha_0 = 35$ [deg] for the environment with $\mu_i = 0.015$ and $\mu_n = 0.6$. However, for the environment with $\mu_i = 0.2$ and $\mu_n = 0.6$, the fastest motion is achieved on, $\alpha_0 = 55$ [deg] for $K_n = 2$, and $\alpha_0 = 45$ [deg].
for $K_n = 3$. As a result, we know that, for the environment with larger ratio of tangential friction coefficient to normal friction coefficient $\mu_t/\mu_n$, the fastest locomotion of our robot is achieved by a smaller initial winding angle $\alpha_0$ due to increasing of the S-shape number $K_n$. The propulsive efficiency is better when $K_n = 2$ than that when $K_n = 3$, and the optimal initial winding angle $\alpha_0$ is changed due to the change of the environment. Fig. 6 shows the motion of our robot in the environment $\mu_t = 0.015$ and $\mu_n = 0.6$, while $\alpha_0 = 35$ [deg]; and Fig. 7 shows that in the environment $\mu_t = 0.2$ and $\mu_n = 0.6$, while $\alpha_0 = 55$ [deg]. It can be clearly seen that our robot did move forward well, and the creeping locomotion curve should be changed corresponding to the change of the environment.

The control algorithm for start and end of the locomotion is also put into practice in our experiment, the motion is shown in Fig. 8.

5. Conclusion

In this study, we presented a new simplified mechanism of a snake-like robot with improved expansibility and adaptability. We suggested that a new simultaneous joint's control method enabled our snake-like robot to change the direction and locomotion speed, while it is in procession. The direct feedback of the robot's locomotion state will also be beneficial in future studies. The new method and structure have been proved to be feasible and advanced through practice. The optimal locomotion shape of our snake-like robot have also been found by experiment.

In our future study, we will develop the sensors to detect the locomotion data in real time in order to better control the motion of our robot. From this point, we will be working on finding a suitable edge to be the connection between the robot and the ground and to further enhance movability, adaptability, and expansibility.
Figure 8. (a) Starting and (b) finishing a crawling locomotion.
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References


Biographies

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